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Beam-forming module for backhaul link in a Relay-aided 4G network

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Abstract: A novel beam-forming module based on Wilkinson power divider technology, including attenuators and phase shifter chips is designed, fabricated and evaluated to be incorporated in a Relay Station connecting him with the Base Station under a 4G network. The proposed module is a 1:8 port circuit, utilizing two substrates, providing approximately 700MHz bandwidth over 3.5GHz frequency band and less than -20dB transmission line coupling. Moreover an external control unit that feeds the beam-forming module with code-words that define the proper amplitude/phase is established and described.

Keywords: Beam-forming, Relay Station, Wilkinson power divider, Attenuators, Phase shifters

I. Introduction

4G wireless networks have received much attention nowadays because they provide high bit-rates and can support high requirement applications such as High Definition video [1]. Under such networks, there are areas of limited or no connectivity due to terrain, building distribution and constrained in-building penetration. In such cases Relay Stations [2] are utilized as transceivers for receiving, enhance and forward signal to the desired direction. These network devices are valid for maintaining high throughput and provide broadband access to end users with a minimum of cost. Fig. 1 depicts the application and usage advantages of Relay Stations.

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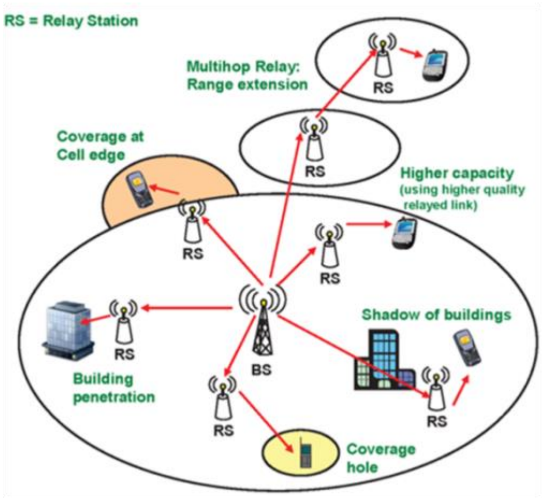

Figure 1: Relay Station operation

A Relay Station (RS) should be equipped with a proper antenna array to communicate with Base Station (BS). Such an antenna array described in [3] should have beam-forming properties to steer the main lobe of radiation to the direction where the BS is placed, establishing in this way the backhaul link. For this reason a beam-forming module for power division and signal processing is required for feeding the antenna array with properly adjusted currents. Such a module has the general form depicted in Fig. 2.

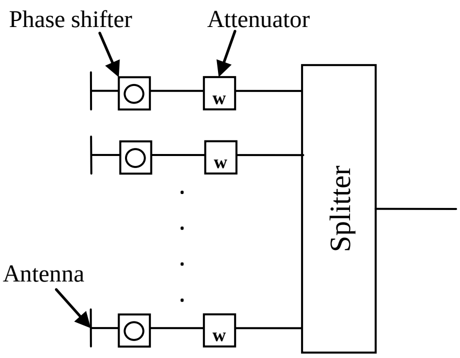

Figure 2: Beam-forming module schematic

Many techniques have been proposed in literature for power division, such as T-junctions [4], 3-dB directional couplers [5] and Wilkinson power dividers (WPD) [6]. The latter technology has been widely investigated, presenting several types and variations. More specifically an 1:2 WPD including stubs for dual band operation has been designed and tested operating at 900MHz and 1.9GHz showing increased bandwidth [7]. In addition a 1:2 WPD with an additional isolation network has been presented providing 4.6GHz bandwidth and low transmission line coupling, testing equal and unequal cases of power split [8]. The case of arbitrary power division ratios was discussed in [9] as well as the WPD harmonic component suppression studied in

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[10]. Furthermore a 5 output port WPD was tested in [11] for 435MHz utilizing lumped elements, providing an isolation of lower than -25dB and a six way WPD based on LTCC substrate, operating in Ka band was designed and evaluated, providing 8.38dB insertion loss [12].
In this paper a small size beam-forming module including the 1:8 WPD and attenuator/phase shifter chips is designed and experimentally evaluated presenting low isolation, below -20dB, operating in the 3.5GHz frequency band to be connected with an antenna array and placed on a Relay Station under a 4G network, realizing the backhaul link. Wilkinson power dividers have been selected as they provide planar configuration, precise power division, good isolation between input and output ports and can be easily connected to other planar devices. The study of the proposed beam-forming module is organized as follows: In section II the beam-forming circuit utilizing Wilkinson power divider technology is described, providing equations where necessary and the included chips for the proper signal processing. Onwards on section III the beam-forming module is tested in terms of the S parameters, considering two scenarios of amplitude/phase combinations and relevant diagrams are depicted and commented. In section IV the external circuit used for the introduction of the amplitude/phase to the corresponded chips is presented and section V includes a summary of the aforementioned study and pointing out some critical parameters.

II. Beam-forming module design and fabrication

In this section beam-forming module is presented providing precise power division and signal processing properties. It is based on Wilkinson power divider technology combined with Surface Mount (SMT) digital chips that appropriately adjust the amplitude and phase of the excitation currents. The proposed module is depicted in Fig. 3.

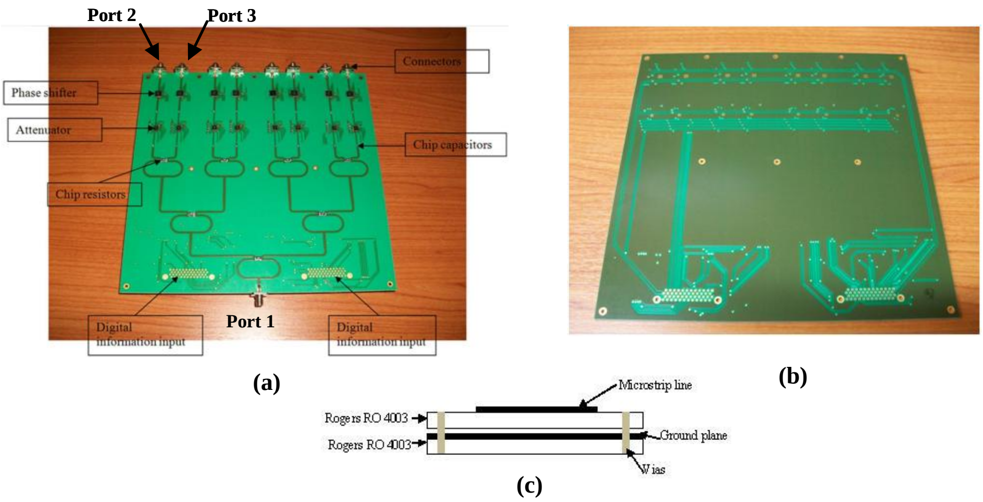

Figure 3: Beam-forming module; (a) Top view (b) Bottom view (c) Cross section

Two Rogers RO 4003 substrates (ε_r=3.55, height h=0.508mm) were used as can be noticed in Fig. 3c. On the top substrate, an 1:8 Wilkinson power divider utilizing microstrip lines is formed, including IMS024 SMT resistors of 100Ω combined with

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HMC629lp4 SMT attenuator [13] and HMC648lp6 SMT phase shifter [14] chips. These chips are loaded with 4 and 6 bit code words respectively that adjust the amplitude and phase of the excitation signal. The code words are defined by an external amplitude/phase control unit and enter the beam-forming module through the Digital information inputs showed in Fig. 3a. The bottom substrate of Fig. 2c holds the ground plane and the digital information transmission lines. The panel has dimensions of 21.2cm×21.8cm.

Basic Wilkinson power divider technology [6] is showed in Fig. 4 where a simple case of 1:2 power division is depicted in terms of the transmission line length and resistance.

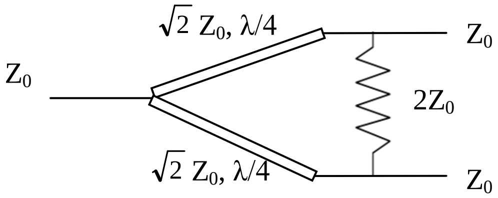

Figure 4: 1:2 Wilkinson power divider

50Ω microstrip lines have been designed using the following formulas found in [15]:

$$L = N\frac{\lambda_g}{4}, \tag{1}$$

$$\frac{W}{h} = \frac{2}{\pi}\{A - 1 - \ln(2A - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}[\ln(A - 1) + 0.39 - \frac{0.61}{\varepsilon_r}]\} \tag{2}$$

where $A = \frac{\pi\eta_0}{2\sqrt{\varepsilon_r}Z_0}$, L the length and W the width of the microstrip lines,

h is the substrate's thickness, ε_r the substrate's permittivity, Z_0 the characteristic impedance of microstrip line, η_0 the free space impedance, N an integer number and λ_g the wavelength in the substrate that is equal to:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}} \tag{3}$$

Microstrip line dimensions have been defined for 3.5GHz resonance frequency, considering Rogers RO 4003 substrate with thickness 0.508mm.

An important issue regarding the beam-forming module design has to do with the incorporation of SMT attenuator and phase shifter chips on the Wilkinson power divider circuit. As can be seen in Fig. 5, the attenuator input and output port is in series connected with 100pF DC blocking capacitors for discarding DC signal components and are also considered as parts of the matching circuit between the transmission line and the input/output of the attenuator. In addition, both phase shifter and attenuator devices are connected with 1000pF and 330pF bypass capacitors respectively placed in parallel with the RF/AC port and the reference ground, where the DC voltage is maintained and the RF signal is short-circuited to the ground [16].

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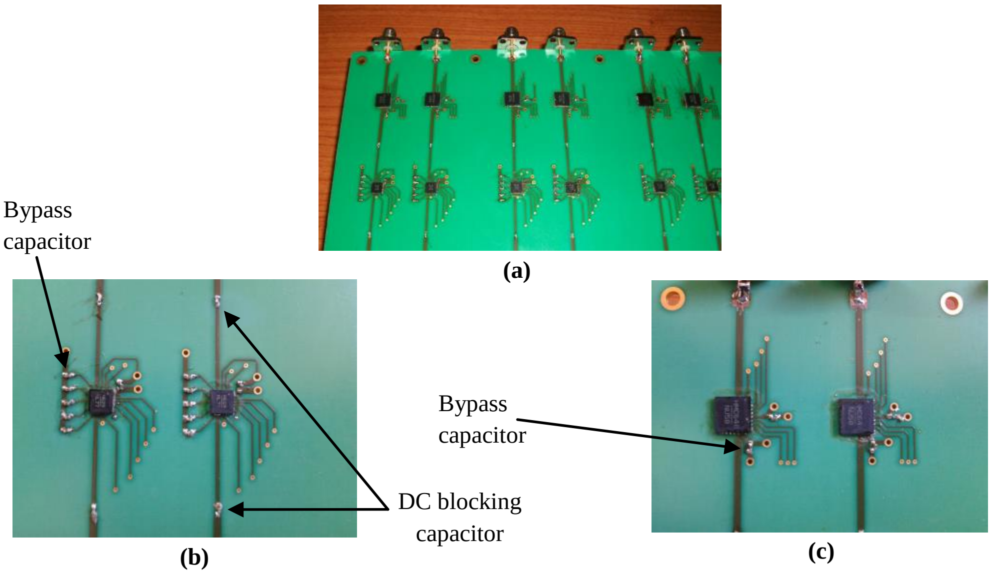

Figure 5: Beamforming module with SMT chips mounted (a) Top view (b) Attenuators (c) Phase shifter

III. Beam-forming module performance evaluation

An external amplitude/phase control unit is used for assigning specific values to the attenuator and phase shifter chips. Then an Anritsu MS6059A VNA instrument is utilized for the experimental measurements of the S parameters of the investigated circuit. This study is especially focused at the 3.5GHz band with a range of 3.3GHz to 3.8GHz. At first all amplitude and phase values are set equal to 0dB and 0deg S_{11} depicted in Fig. 6.

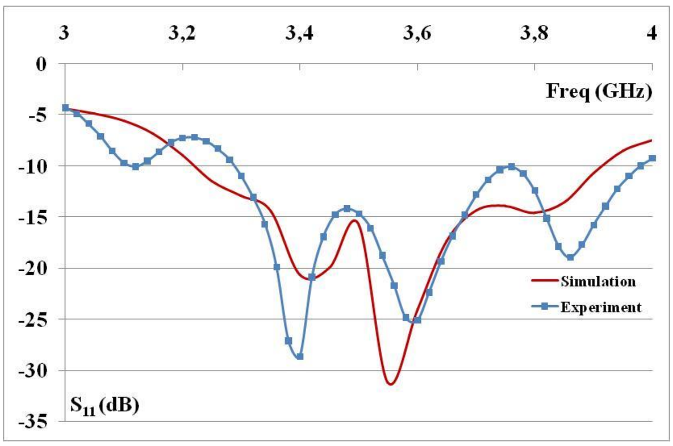

Figure 6: S_{11} of the beamforming module

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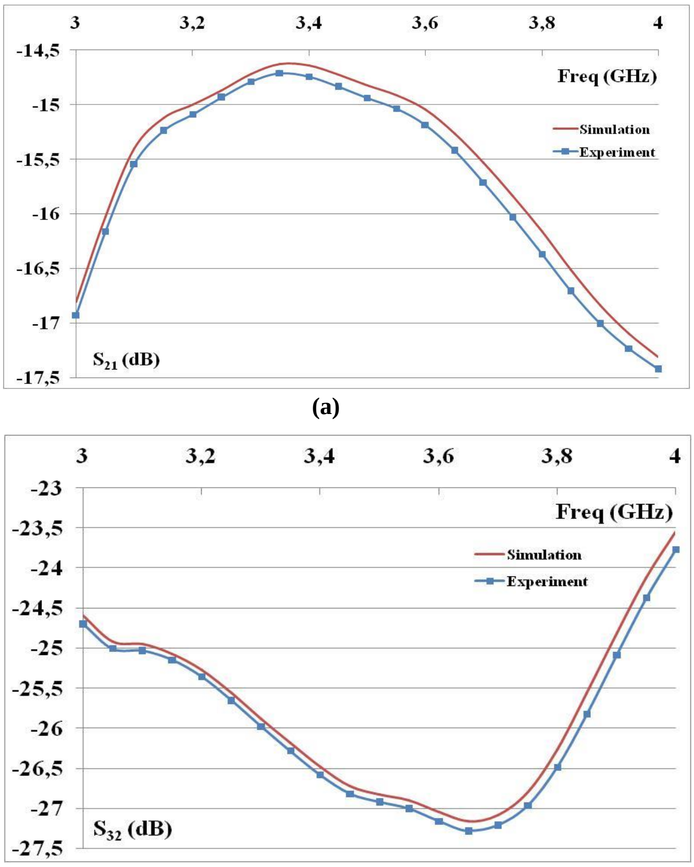
Beam-forming module operated in the frequency range from 3.3GHz to 4GHz, presenting 700MHz bandwidth (S_{11}<-10dB) with a minimum of S_{11}=-27.1dB at 3.4GHz. Onwards insertion loss in terms of S_{21} and isolation in terms of S_{32} are presented in Fig. 7.



(a)

(b)

Figure 7: S parameters of the beam-forming module; (a) Insertion loss S_{21} (b) Isolation S_{32}

Experimental insertion loss depicted in Fig. 7a, varies from -16.4dB for 3.8GHz to -14.7dB for 3.35GHz while the experimental isolation approximates -27.3dB for 3.65GHz and reaches -26dB for 3.3GHz. S_{32} parameter is adequately low, less than -20dB for the frequency range of interest, proving low coupling between microstrip lines. On the other hand S_{21} reaches approximately -15dB attenuation as a result of power division, SMT chip incorporation and SMA connector mismatches.

The evaluation of the beam-forming module is continued considering a combination of amplitudes and phases which are assigned to the corresponded chips providing simulation and experimental results depicted below. The amplitude/phase combination scenario is included in Table 1.

Table 1: amplitude/phase scenario

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Chip	1	2	3	4	5	6	7	8
Amplitude (dB)	0	-3	-3	-6	-6	-9	-9	-12
Phase (deg)	0	16.875	33.75	61.875	73.125	73.125	0	0

The above values of amplitude and phase are inserted in the chips of the beam-forming module and S_{11} parameter is depicted in Fig. 8.

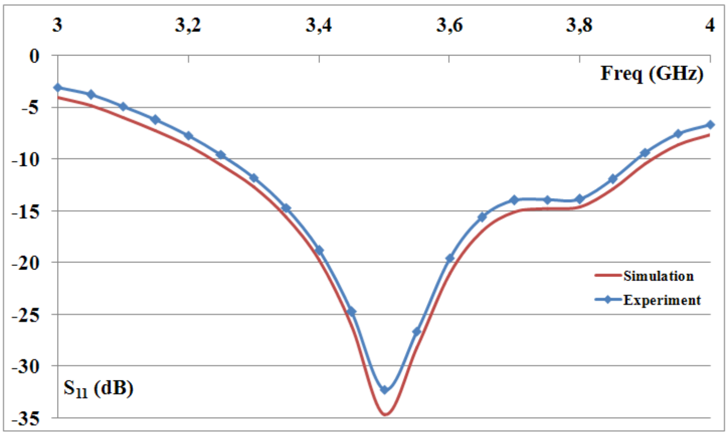
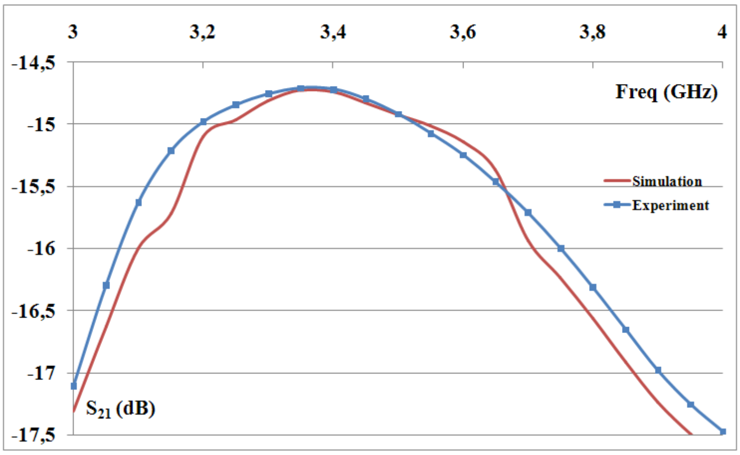
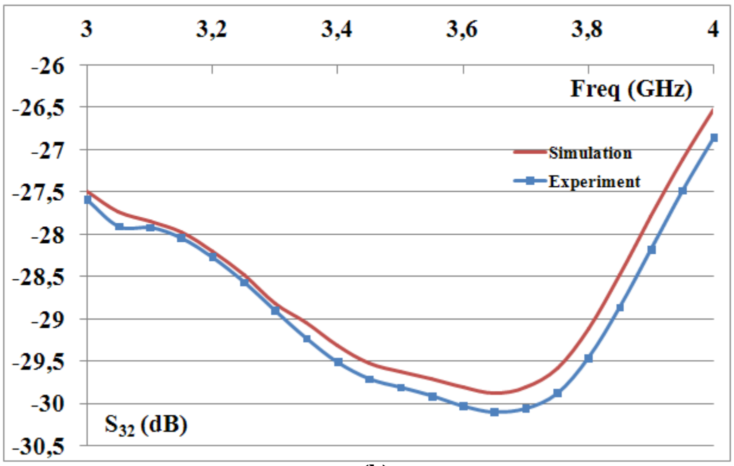


Figure 8: S_{11} of the amplitude/phase scenario of Table 1

Beam-forming module presents S_{11}=-32.2dB for 3.5GHz and a bandwidth of 650MHz, from 3.25GHz to 3.9GHz that overcomes the required bandwidth. Onwards the insertion loss and isolation is assessed for the same scenario of amplitude/phase and depicted in Fig. 9.



(a)



(b)

Figure 9: S parameters of the beam-forming module for the amplitude/phase scenario of table 1; (a) Insertion loss S_{21} (b) Isolation S_{32}

Experimental insertion loss (S_{21}) is equal to -14.7dB for 3.35GHz and -16.3dB for 3.8GHz while S_{32} reaches -28.9dB for 3.3GHz and -30.1dB for 3.65GHz. Other graphs of have been obtained for several amplitude/phase scenarios showing similar S parameter behavior, proving the stability and efficiency of the beam-forming module.

IV. Amplitude/phase control unit

The beam-forming module depicted in Fig. 3 is externally fed by an amplitude/phase control unit. This unit includes:

- AVR EVK 1100 microcontroller of Atmel,
- 74HC154 chip (4 to 16 line decoder/demultiplexer),
- 74VHC139 chip (dual 2 to 4 decoder/demultiplexer)
- 74LS164 chip (serial in parallel out shift register)

Microcontroller is used for defining the proper 4 bit and 6 bit codeword that corresponds to an amplitude and phase value to be inserted to the beam-forming module. Two decoders are incorporated for selecting the appropriate attenuator and phase shifter chip that will accept the codeword and finally shift registers are included for the transformation of bit stream into parallel form and then enter into the chips. Fig. 10 depicts the proposed control unit configuration.

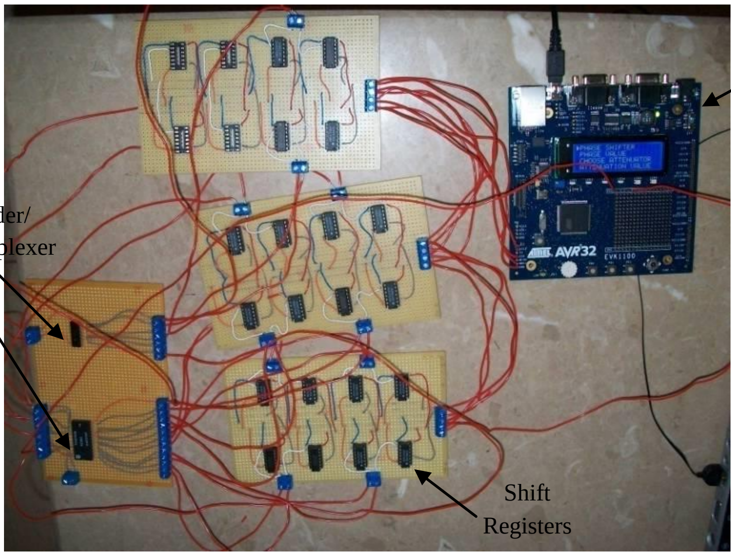


Figure 10: Amplitude/phase control unit

Shift registers shown in Fig. 10 are connected to the digital information input shown in Fig. 3a through wires carrying the necessary codewords to the proper attenuators and phase shifters. In this way amplitude and phase adjustments take place in RF level simplifying in this way signal processing. Moreover the utilization of digital chips provide some advantages such as low size, quick amplitude/phase change, low losses, low power requirements and high amplitude/phase accuracy.

V. Conclusions

In this study a beam-forming module for the backhaul link realization was designed, fabricated and tested for a Relay-aided 4G network. This module utilizes a two substrate planar configuration including Wilkinson power divider microstrip circuit and SMT attenuators and phase shifter chips. For the case of setting 0 dB amplitude and 0 deg phase, the beam-forming module is tested in terms of S parameters and results prove operation from 3.3GHz to 4GHz with resonance at 3.4GHz. Experimental S_{21} varies from -16.4dB to -14.7dB while S_{32} changes from -27.3dB to -26dB in the frequency band of interest (3.3GHz to 3.8GHz). A second case of amplitude/phase combination is considered and S parameters are also obtained and depicted. S_{11} provides a bandwidth of 650MHz from 3.25GHz to 3.9GHz while S_{21} varies from -16.3dB to -14.7dB and S_{32} from -30.1dB to -28.9dB within the specified frequency band.

The proposed beam-forming module has a planar small size configuration making in this way easy the installation procedure on a Relay Station. Besides this it provides

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efficient power division in the frequency range of interest, high microstrip line isolation and operation in a wide range of amplitude/phase combinations. Two such modules can be used in a parallel form connected via SMA cables with an array presented in [3] to provide a phased array system which can be used in Relay-aided WiMAX network for backhaul link realization. The proposed phased array setup can be seen in Fig. 11.

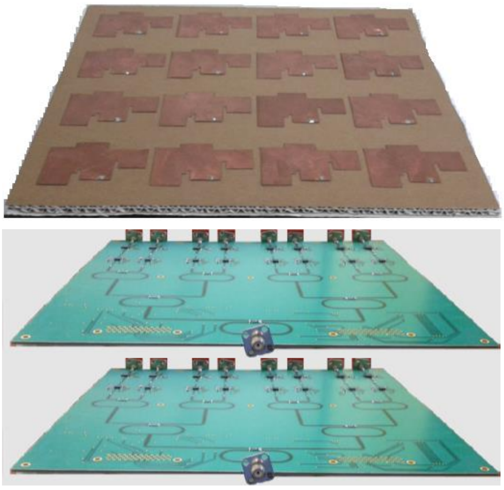

Figure 11: Phased array setup

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Short biography

Dr. Ioannis Petropoulos

Ioannis Petropoulos was born in Athens, Greece in 1979. He holds a BSc in Physics from University of Patras. He received his MSc degree in data communication systems from Brunel University in collaboration with Technological Educational Institute of Athens (TEI-Athens) in 2007. He is PhD candidate in the University of

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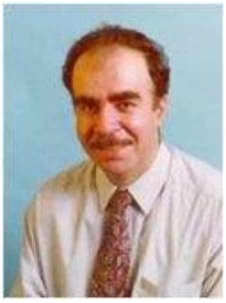
Bradford (UK) in collaboration with Technological Educational Institute of Athens (TEI-Athens). He is Research Assistant of the Wireless Communication and e-applications research group in the department of Electronics in TEI-Athens. He participated in fp7 program “REWIND” (Grant Agreement no. 216751) funded by European Communion with aim the design and fabrication of a Relay Station for a WiMAX network. He has also took part in the project: “NexGenMiliWave”, (project code MIKRO2-SE-B/E-II) funded by ESPA 2007-2013 with aim the design and fabrication of a millimeter wave radio modem. His scientific interests include smart antenna design, millimeter and microwave RF front-end design and EMC testing.

Prof. Konstantinos Voudouris

Prof. Konstantinos Voudouris, PhD (U.Bradford), Dipl.Ing. (U.Patras), BSc (TEI of Athens), is Associate Professor within the Department of Electronics Engineering of the Technological and Educational Institute (TEI) of Athens, Greece, and heads the Wireless Communications & eApplications Research (WiCEAR) Laboratory. Before, he worked in UK, Cyprus, Greece and Belgium as a telecoms expert. He coordinated the FP7 ICT REWIND project, focusing on the development of a Relay Station (RS) prototype for IEEE 802.16j WiMAX networks. He scientifically leads the WiCEAR group, in NexGenMiliwave project (development of a 60GHz transceiver) within the concept of Corallia Cluster. Dr. Voudouris has published over 75 scientific papers in international journals and conferences.

Prof. Raed A Abd-Alhameed



Raed A Abd-Alhameed is Professor of Electromagnetic and Radio Frequency Engineering at the University of Bradford, UK. He received the B.Sc. and M.Sc. degrees from Basrah University, in 1982 and 1985 respectively, and the Ph.D. degree from the University of Bradford, UK, in 1997, all in electrical engineering. He has long years’ research experience over 25 years in the areas of Radio Frequency, antennas and electromagnetic computational techniques, and has published over 400 academic journal and conference papers; in addition he is co-authors of two books and several book chapters. He is the senior academic responsible for electromagnetics research in the communications research group.

Dr. Steve Jones

Steve Jones lecturers in Telecommunications and is Director of Studies for programmes in Electronics and Telecommunications in the School of Engineering, Design and Technology at the

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University of Bradford. Since joining the University in 1987, he has worked on a wide variety of research projects in the area of satellite slant-path propagation (e.g. 10 GHz bistatic-scatter, 11/14 GHz scintillation and ice depolarization with Olympus) and mobile radio propagation (notably Mobile VCE and TEAMS projects). He served as an Associate Editor for the IEEE Transactions on Antennas and Propagation 2004-8. Recent work includes a Knowledge Transfer Partnership with PACE developing MIMO antenna technology for set top boxes.